Review of study on mineralization, saturation and cycle of Nitrogen in forest ecosystems

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Abstract: Nitrogen is one of the most important elements that can limit plant growth in forest ecosystems. Studies of nitrogen mineralization, nitrogen saturation and nitrogen cycle in forest ecosystems is very necessary for understanding the productivity of stand, nutrient cycle and turnover of nitrogen of forest ecosystems. Based on comparison and analysis of domestic and international academic references related to studies on nitrogen mineralization, nitrogen saturation and nitrogen cycle in recent 10 years, the current situation and development of the study on these aspects, and the problems existed in current researches were reviewed. At last, some advices were given for future researches.

Keywords: Nitrogen; Nitrogen mineralization; Nitrogen saturation; Climate change; Nitrogen cycling

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Introduction

Nitrogen is an important element that not only contributes to the plant growth and development, but also is the biggest amount of elements that plants absorb from the soil as well (Ingestad 1981). At the same time, it is easier to leach out or volatilize from the forest soil than other elements (Rashid & Scheafer 1988). Recently, people started to know that human activity, such as industrial pollution, disturbance of ecosystems and widespread application of nitrogen fertilizer, have had a significant effect on the global nitrogen cycle (Boring *et al.* 1988; Vitousek *et al.* 1997). Moreover, there are many theories and mechanisms of nitrogen cycle in forest ecosystems (Friedland *et al.* 1991; Treseder & Vitousek 2001; Perakis& Hedin 2002). The studies of nitrogen mineralization, nitrogen saturation and nitrogen cycle is very necessary for understanding the mechanism of nitrogen cycle, productivity, nutrients cycle and turnover in forest ecosystems.

This paper compared and analyzed domestic and international academic literatures of recent 10 years related to studies on nitrogen mineralization, nitrogen saturation and cycle, the current situation and development of the study on these aspects in China, and the problems existed in current researches. The following four aspects are manly discussed in the paper: 1) nitrogen mineralization; 2) effects of climate change on nitrogen mineralization; 3) nitrogen saturation, and 4) nitrogen cycle in forest ecosystems.

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Nitrogen mineralization

Nitrogen mineralization means a process that nitrogen turned into inorganic nitrogen (NO_3-N and NH_4-N) from organic nitrogen with the help of soil animals and microorganism. Inorganic nitrogen is the main type of soil nitrogen that can be directly absorbed and utilized by plants, but only accounting to 1% in the total soil nitrogen (Das 1997). The nitrogen mineralization rate determines the availability of nitrogen for plant growth. The nitrogen mineralization process is one of the most important processes for nitrogen cycle in forest ecosystems, and it demonstrates the nature of functions of ecosystem and biogeochemical cycle. The importance of nitrogen mineralization lies in: 1) nitrogen availability restricts the nitrogen-use-efficiency of plants so that affects the productivity of terrestrial ecosystem; 2) there is a feedback relationship between nitrogen availability and community succession; 3) the nitrogen mineralization influences the leaching and gaseous loss of nitrogen in forest soil and thus affects the environmental pollution and economic use of nitrogen; and 4) the discharge of nitrate is one of the important reasons of greenhouse effects and global warming (Li *et al.* 2001).

The study of nitrogen mineralization initiated at the 1960s. The relevant research have been continued and pursued in subsequent years. Many reviews on nitrogen mineralization were issued in the academic journals and websites. Nitrogen mineralization depends on many factors, such as soil temperature (Bonde *et al.* 1987; Powers *et al.* 1990; Nadelhoffer *et al.* 1991; Ineson *et al.* 1998), humidity (Smith *et al.* 1998; Evans *et al.* 1998; Jamieson *et al.* 1999), physical and chemical characteristics of soil (Groffman *et al.* 1996; Rovira *et al.* 1997; Priha *et al.* 1999), litter (Liu & Muller 1993; Fyles *et al.* 1990), soil animals and microor-

ganism (Ferris *et al.* 1998; Holmes & Zak 1994; Beare *et al.* 1992; Sulkava *et al.* 1996), vegetation type (Ohrui *et al.* 1999; Berendse *et al.* 1990; Verhoveven *et al.* 1990), temporal and spatial scale, and other disturbances (Reich *et al.* 1997). Here we mainly summarized the effects of soil temperature and humidity on nitrogen mineralization.

Soil temperature and humidity are two most important factors influencing and controlling the nitrogen mineralization, and there is a positive feedback between them. High temperature and dryness are favorite conditions for nitrogen mineralization (Wilson & Jefferioes 1996). Nadelhoffer *et al.* (1991) concluded that the nitrogen mineralization rate was sensitive to temperature range of 3-9 °C and increased with temperature rising from 9°C to 15°C; and differences of the rates which caused by temperature in different soil types was more than in single soil cultivation. Ineson *et al.* (1998) utilized a controlled temperature system to test the nitrogen mineralization, they found that NO_3^-N significantly decreased with increasing the soil temperature of 3-5°C. The increase of temperature not only accelerated the soil nitrogen mineralization but also speeded up the plant for absorption of nitrogen.

There is a positive relationship between net nitrogen mineralization and soil humidity (Evans *et al.* 1998). Stanford (1974) showed that the nitrogen mineralization increased as the increase of water potential; when water potential was in -1.5 MPa—-0.03 MPa, the relationship between nitrogen mineralization and soil humidity was linear, the maximum appeared in -0.5 MPa—-0.03 MPa, the optimal value was in -0.03 MPa—0.01 MPa. There is a seasonal fluctuation in total nitrogen mineralization, and the precipitation of summer may be the main reason of influencing the nitrogen flux (Jamieson *et al.* 1999). When the soil was full of water in humid period, the fixation of NH_4-N was more than that of nitration and the net mineralization decreased (Marrs *et al.* 1991).

In a word, nitrogen mineralization increased with the increase of temperature in limited temperature range. The nitrogen mineralization was promoted by increasing soil water content and declined after reaching the maximum. At the same time, the water fluctuation accelerated the nitrogen mineralization (Li *et al.* 2001).

Effects of climate change on nitrogen mineralization

The changes of global climate have been an important research fields for many researchers. The increase of carbon dioxide and global warming affecting nitrogen turnover and utilization became more and more important in the issues of global climate change. These changes have effects on C/N ratios and dynamic processes of nitrogen in soil–plant– atmosphere systems, and the increase of carbon dioxide and global warming will influence and change the environmental (e.g. temperature and humidity) and biological (e.g. vegetation type and organism diversity) conditions for mineralization, turnover and cycle of nitrogen (Zhang 1998). In addition, the increases in the supply of bio-available nitrogen may have a fertilizing effect on many nitrogen-limited terrestrial ecosystems since it increased ecosystem productivity (Townsend *et al.* 1996). Other nutrients may determine the extent of increased productivity due to carbon fertilization; Oren *et al.* (2001) found that increased nitrogen availability may lead to higher net primary productivity. As to effects of the global warming, it was partly mentioned above (temperature influencing nitrogen mineralization). Generally, accelerating carbon dioxide and global warming may change the input ratio of carbon and nitrogen, especially for transformation in forest ecosystem soil and the feedbacks of nitrogen mineralization and potential leaching and utilization of nitrogen. Because of the uncertainties in the climate change, the magnitude and relative importance of causing effects of these uncertain factors are difficult to be determined.

Nitrogen saturation

The lack of nitrogen is a very common problem in global forest ecosystems, and especially it can limit the development of forest ecosystems. However, the acid deposition has been a global environmental problem since the 1970s. Human activities (eg. industrial pollution and widespread application of nitrogen fertilizer) may significantly influence the global nitrogen cycle (Boring *et al.* 1988; Vitousek *et al.* 1997). Moreover, high emissions of N to the air through combustion (NOx) and volatilization processes (mainly NH_3 from agricultural practices) in the later part of the 20th Century, has now shifted the focus to the problem of N excess (Berge *et al.* 1999). On this issue, there are two concepts about nitrogen saturation. Firstly, Ågren and Bosatta (1988) defined N saturation as the stage when N losses equal N deposition and the system has no further capacity to retain N, and then Aber *et al.* (1989) used the same term for ecosystems in which availability of inorganic N exceeds the demand from microorganisms and plants, thus eventually leads to nitrate leaching with runoff water. The timing of N saturation, defined in either way, depends on N deposition rates as well as land use, both current and historical (Gundersen 1991; Aber *et al.* 1997). A great amount of references showed that human activities have dramatically increased the emission of fixed nitrogen compounds to the atmosphere and the accelerating deposition of fixed N across large regions in the temperate zone, particularly in western Europe, eastern Asia, and the eastern U.S. (Galloway *et al.* 1995; Holland *et al.* 1999; Vitousek 1994). Therefore, two important projects that EXMAN (Experiment Manipulation of Forest Ecosystems in Europe, 1988-1991) and NITREX (Nitrogen saturation Experiments, 1991-1994) were carried out in European countries. The projects involved 12 experimental sites in 8 countries. They reported that inputs of N exceeding biotic demand have negative effects on ecosystems, the effects of increased nitrogen deposition in atmosphere on forests included: endangered the structures and functions of forest

ecosystems; changed tree physiology and led to soil acidification and nutrient unbalances; influenced the intra-specific competition dynamics and decelerated the resistance to environmental stresses; and the nitrogen saturation was reached by the nitrogen input over 25 kg·hm^{-2} (Bredemeier *et al.* 1998; Boxman *et al.* 1998; Emmett *et al.* 1998).

Many different indices of N status have been proposed, *e.g.* foliage N concentration, soil N concentration, soil N pool, soil C/N ratio, net N mineralization (Gundersen *et al.* 1998), to monitor and test ecosystems change towards N saturation. Aber *et al.* (1997) suggested that net N mineralization relative to a site/species-specific maximum sustainable net N mineralization would be a better index than the net N mineralization itself. Gundersen *et al.* (1998) reported that high N leaching was likely to occur at forest floor when the C/N-ratios was below 30%; Aber *et al.* (1997) found that a relative mineralization (current net N mineralization/ maximum sustainable net N mineralization) greater than 75% was at risk of nitrate leaching.

With the help of application experiments of fertilizer in forests in the northeastern U.S., Aber *et al.* (1998) found that increasing N deposition led to the increase of nitrification, leaching of nitrate, higher foliar nitrogen content, and a decrease in net primary productivity when the ecosystem was saturated with nitrogen. The increase in leaching can augment nitrogen supply to ecosystems downstream, and the increased transport of nitrate out of the soil can increase the acidity of soil and water, simultaneously leach mineral cations such as Al, Ca, K, and Mg from the soil (Vitousek *et al.* 1997). Artificially increasing N deposition was also detrimental to plant species that are suitable for efficient N use, and it decreased N fixation and mycorrhizal infection (Boring *et al.* 1988). Despite the increase in nitrate and nitrate leaching, Aber *et al.* (1998) found that more nitrogen was retained by the experimentally altered forests than it was expected. This result may be due to increasing rates of assimilation and immobilization by mycorrhizae. Townsend *et al.* (1996) hypothesized that if N fertilization were carried out on a large-scale, the growth rate of forest would eventually diminish. The reason was that excess N could not continue to stimulate growth, and carbon storage was contracted due to N fertilization.

In addition, there are several ways of forest declining due to excess nitrogen. They included an excess assimilation of inorganic N "stealing" carbon that otherwise could be used for growth and maintenance, an increased shoot/root ratio and related drought and wind problems, increased intensity and frequency of insect and pathogenic pests and nutrient deficiency and/or aluminium toxicity due to acidification by nitrification could all lead to impaired production (Andersson *et al.* 2001).

Nitrogen cycle

As to the nitrogen cycle in forest ecosystems, dynamics and the mechanism of nitrogen cycle were reported in many researches (Vitousek *et al.* 1997; Ohrui *et al.* 1999). Conceptual and numerical models of nitrogen cycle in temperate forests suggested that nitrogen is lost from these ecosystems predominantly by way of inorganic forms, such as nitrate and ammonium ions (Friedland *et al.* 1991). The nitrate is thought to be particularly mobile, being responsible for nitrogen loss to deep soil and stream waters. Adversely, it was found in other studies that organic nitrogen forms are responsible for nitrogen cycle in forest ecosystems. Due to slow decomposition, the release rate of available forms of organic nitrogen (the main soil N pool) limited the plant growth (Ågren and Bosatta, 1988). However, forest ecosystems in areas with a natural (low) N deposition are dominated by organic N. Not only is the soil pool mainly organic, but dissolved N in soil water and N lost in runoff are dominated by organic N forms as well (Hedin *et al.*, 1995). Many experiments supported that uptake of organic N by mycorrhizae might be important for N nutrition in forests because many plants and mycorrhizal fungi may take up, *e.g.* amino acids (Schimel and Chapin, 1996; Näsholm *et al.*, 1998). Researchers have taken on the experiments of processes of the nitrogen cycle in relatively unpolluted ecosystems, such as the temperate coastal forests in southern Chile and tropical mountain forests in Hawaii (Perakis & Hedin 2001; Treseder & Vitousek 2001). These studies reported the high levels of nitrate both within an ecosystem and in the outputs are the result of increasing N deposition from human activities in unpolluted temperate forests of South American (Hedin *et al.* 1995; Perakis & Hedin 2002). Perakis & Hedin (2002) sampled 100 first-order streams that drained small watersheds within 13 different geographical areas, they concluded export of DON (dissolved organic nitrogen) which offers a mechanism to explain why nitrogen commonly limits plant productivity and carbon sequestration in moist temperate forests, in which were with naturally low inputs of nitrogen from atmospheric deposition and nitrogen fixation. Therefore, it is considered that models of forest ecosystems should include DON as a central pathway of nitrogen loss, and should take into account the effects that such losses may have on nutrient limitation and carbon balances. Contrary to the current theory and mechanism of nitrogen cycle, these studies are important because they provide baseline knowledge of ecosystem nitrogen cycle prior to artificially nitrogen deposition.

Research development in China

The study of nitrogen in China mainly focuses on agricultural systems (rice, wheat and soybean) and most of them are a research of single process. There are relatively few researches about nitrogen in forest system (Fu *et al.*1995; Sha *et al.* 2000; Su *et al.* 2001). Although there were several reviews (Jiang 1997; Li *et al.* 2001; Zhang 1998) and papers (Mo *et al.*1997a, 1997b; Yu *et al.* 1995;

Meng *et al.* 2001) on nitrogen mineralization, these papers and researches mainly focused on nitrogen mineralization in different vegetation types (pure pine forest; pine-oak mixed forest; pine-broadleaf mixed forest; alder and cypress mixed forest; fir plantations), and the researches mostly carried out in tropical (Sha *et al.* 2000; Meng *et al.* 2001) and subtropical regions (Mo *et al.* 1997a, 1997b; Yu *et al.* 1995). The boreal forest in China was little concerned (Su *et al.* 2001). At the same time, with the nitrogen fertilization and industrial pollution, the south part of China has been the third nitrogen deposition in the world, however the literature of nitrogen saturation was relatively little (Fan *et al.* 2000). As to the nitrogen mineralization, it is difficult to compare and analyze most experimental materials because of the width and depth, the short-term experimental period and lack of interactions with other factors restricted the general conclusion.

Problems and advices

1) Because of the various conclusions and the flaw of the theory and mechanism of nitrogen cycle in forest ecosystems, more attention should be paid to natural and original forests, and thus it may provide useful bases for the theory of nitrogen cycle.

2) There are some uncertainty factors in global climate changes that lead to those of nitrogen utilization in forest ecosystems; therefore, we should strengthen the study of nitrogen mineralization and utilization under the conditions of global climate change.

3) Evaluating the problems concerning N turnover, N deposition and N saturation, most studies and models usually only consider inorganic nitrogen species, however, there are no attempts to consider uptake of organic N, we should strengthen the study of organic nitrogen and provide a full-scale of research for dynamic nitrogen processes in forest ecosystems.

4) Being short of studies on interacting processes in soil-plant-atmosphere systems, especially in China, the experimental results were different and difficult to explain, and their need more detailed research in future.

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